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Description

Optical filter, adjustable add-drop-continue module and circuit arrangement for bundled cross-connect functionality

The invention relates to a tunable optical filter and to an add-drop module according to the preamble of claim 7 which is produced using this filter, to an add-drop device and to a circuit arrangement for bundled cross-connect functionality.

In order to ensure minimal interference during signal transmission, optical wavelength multiplex networks (WDM networks) are redundantly designed. Ring structures are often provided. At a junctions between different rings, "drop-and-continue" functions are implemented, i.e. the signal is split and is both forwarded through the original ring and transferred into the new ring. For purely optical production of a drop-and-continue function, it is possible to use wavelength demultiplexers, optical switches and wavelength multiplexers.

For the production of add-drop functions, modules from the company High Wave Technologies are known, which consist of two circulators with interposed tunable filters. In the event of tuning due to a configurational change, however, the retuning of one WDM channel generally interferes with the signals of other WDM channels. These modules are not intended for drop-and-continue functions. It is, however, conceivable to supplement this module with splitters and switches, in order to produce the drop-and-continue function.

Figure 1 represents such an "add-drop-continue module". It consists of a splitter SP, which

divides the optical signal into two signals of roughly equal strength. One component is fed via two circulators having a tunable filter connected in between. In order to produce the drop-and-continue function, one signal component D_k is branched off via the first circulator and the other signal component C_k is forwarded via an optical switch SW (the switch position which is represented).

In the case of an add-drop function, one signal component D_k is likewise branched off, but a new signal A_k having the same wavelength is simultaneously inserted via the second circulator ZI2. Owing to the use of the optical splitter, the module has in principle an attenuation of at least 3 dB. Depending on the number of add-drop functions, the aforementioned add-drop element is multiply connected in series, so that the attenuation is further increased significantly.

The cross-connect functionality in optical multi-wavelength multiplex systems (WDM) is needed so that a specific wavelength signal of an incoming multi-wavelength signal can be distributed in any desired direction.

"WDM Gridconnect - ein transparentes faseroptisches Kommunikationsnetz mit Faser- und Wellenlängenmultiplex" [WDM grid-connect - a transparent fiber-optic communications network having fiber and wavelength multiplex] by Hubert Anton Jäger, published by Hartung-Gorre-Verlag, Constance [Germany] 1998 describes a standard optical cross-connect (OXC). Such an optical cross-connect (OXC) having optical n x n space-switching subunits with n incoming bidirectional multi-wavelength signals, each having k wavelengths, is represented in Figure 9. In this case, the optical multi-wavelength signal is decomposed by means of optical wavelength demultiplexers DMUX into k single-frequency signals which are subsequently switched to any desired output of the space-switching subunit by using optical space-switching subunits of dimension n x n. The single-frequency signals coming together

from the outputs of the space-switching subunits are coupled and forwarded by means of a multiplexer MUX.

A disadvantage with this is the large outlay on equipment which is incurred when making these optical cross-connects (OXC). A circuit arrangement having, for example, 64 wavelengths per multi-wavelength signal and 4 bidirectional conductors needs 64 space-switching subunits of dimension 4 x 4. Furthermore, 64 fiber-optic connections to the corresponding space-switching subunits of dimension n x n have to be installed per multiplexer MUX and demultiplexer DMUX, respectively, plus the same number again from the space-switching subunits to the demultiplexers DMUX or multiplexers MUX on the other side.

JP 1 023 479/US 5 963 685 describes an add-drop module which contains a plurality of reflection filters whose frequencies can be adjusted by mechanical pressure and changing the temperature.

The patent US 5,707,375 likewise specifies an add-drop device whose filters have different and mutually asymmetric edges. By tuning the filters in terms of wavelength, it is possible to obtain complete transmission, complete reflection or partial transmission and reflection. In this solution, it is necessary to have double the number of filters and adjustment devices. However, readjustment of the wavelength during operation leads to interference with the other signals.

The European patent application EP 0854 378 A2 describes a thermal-optical component which has a splitter and a tunable grating filter. The arrangement operates as an optical switch and can be used to produce add-drop functions.

The patent US 5,408,319 describes an optical demultiplexer in which tuning to a specific wavelength is carried out not mechanically but by changing the temperature.

The patent application WO 98/04854 describes an add-drop module which can be tuned by heating strips or magnetoresistors.

WO 99/42893 also discloses a tunable add-drop multiplexer. In order to tune the wavelength, the refractive index of the filter material is changed, for example by heating.

The known principles are unsuitable or too elaborate for producing an add-drop-continue function.

It is an object of the invention to propose an add-drop-continue module having little attenuation, as well as a filter which is suitable for its production and has a variable transmission characteristic. This module is also intended to permit reconfiguration of channels without causing interference.

It is another object of the invention to propose a circuit arrangement having cross-connect functionality, which allows simple allocation of dynamically assembled multi-wavelength bundles to different conductors. It is another object of the invention to propose a circuit arrangement having cross-connect functionality, which permits reduced complexity of the system. In this case as well, reconfiguration of channels is intended to be made possible without causing interference.

The object is achieved by a filter specified in claim 1, an add-drop-continue module specified in claim 6 and a "cross-connect module" for producing bundled

cross-connect functionality as claimed in the dependent claims. Variants of this module are furthermore specified.

Advantageous refinements are specified in the dependent claims.

The special advantage of the module, and of the circuit arrangement for producing bundled cross-connect functionality, is due to the filter whose frequency and attenuation can be varied. This not only makes it possible to select different channels: no optical switches are necessary for producing add-drop, drop-continue or cross-connect functions. Reconfiguration of the network can be carried out without interference to adjacent signals.

In particular, the invention is achieved by an optical filter, wherein a device (HE) is provided for adjusting the transmission response by means of a deliberate temperature change. The effect achieved by adjusting the transmission response through temperature changes is that the optical filter is non-destructively reconfigurable, which has never before been possible in the case of purely optical network elements except with expensive optical circuit technology (wavelength multiplexers, wavelength demultiplexers, space-switching matrices). In contrast to standard wavelength filters, the transmission attenuation can also be adjusted in addition to the resonant wavelength in the optical filter according to the invention.

In another preferred exemplary embodiment of the optical filter, at least two regions (B1, B2) in an optically transparent material, which have different temperature-dependent refractive indices n_1 (t) and n_2 (t), are essentially involved in the optical waveguiding and/or the filter action, and wherein the difference between the refractive indices n_1 (t) and n_2 (t) is at least approximately zero at one temperature within the temperature-controllable working range. The temperature-dependent difference in refractive index between two optical materials is hence influenced by the deliberate change of temperature. This exploitation of the

thermo-optical effect to influence the quality factor of the resonance is performed by adjusting the resonant wavelength λ_k and the transmission attenuation d for this wavelength. On the grounds of conservation of energy, the reflection factor is obtained directly from the transmission response in the ideal case. Energy components which are not transmitted must necessarily be reflected. The resonant wavelength λ_k is essentially influenced by the period Λ of the interfaces. The transmission attenuation is given essentially by (besides the grating length Z and the grating amplitude) the difference in refractive index $n_1 - n_2$.

The optical filter according to the invention is advantageously designed in planar technology. This facilitates integration into existing circuitry. The optical filter is furthermore preferably produced as a fiber grating. The difference in refractive index between two optical layers involved in the waveguiding is of essential importance in the case of fiber gratings as well. The principle employed here, namely to influence the transmission attenuation by a thermal refractive-index change, may therefore preferably be used in the case of such filters as well.

An optical filter is particularly preferably designed as a tunable band-stop filter. This facilitates the extraction of a frequency band. The latter is advantageous especially in purely optical telecommunications networks.

The tuning of the band-stop filter is particularly preferably carried out by mechanical pressure, tension or bending. By means of this, the wavelength to be filtered in the optical spectrum can be selected by exposing the band-stop filter to mechanical influence.

The invention is furthermore achieved by an add-drop-continue module having an optical filter according to the invention,

wherein the tunable optical filter (BSF) is arranged between a branching device (ZI1) for optical signals and an insertion device (ZI2, KO). By means of this, an add-drop-continue module can be constructed using an optical filter according to the invention. The signal is split in the branching device for optical signals, and one component is fed to the gate of the optical filter according to the invention. The component to be extracted is reflected and forwarded, whereas the component to be injected is inserted by the insertion device (ZI2, KO).

In another preferred add-drop-continue module of the present invention, a plurality of optical filters (BSF1 to BSFM) are arranged between a branching device (ZI1) for optical signals and an insertion device (ZI2, KO). By means of this, it is possible for a plurality of individually adjustable optical spectra to be extracted from the signal and, particularly preferably, to the injected or re-extracted via multiplexers and demultiplexers, respectively.

In another preferred add-drop-continue module of the present invention, circulators are provided as the branching devices (ZI1) and as the insertion device (ZI2). By means of this, the injection and extraction of the signals can be carried out using known hardware components. Triple circulators are preferably used for this. Quad circulators are particularly preferably used. It is also possible to use Mach-Zehnder structures.

The object of the present invention is particularly preferably achieved by an add-drop-continue device, wherein a plurality of series-connected add-drop modules of the present invention are provided. By means of this, it is possible to fulfill a very wide variety of circuit tasks within purely optical networks.

In another preferred drop-and-continue module having an optical filter according to the invention, the optical filter is connected downstream of a branching device for optical signals. By means of this, it is possible to produce the drop-and-continue functionality by using purely optical hardware components.

The invention is furthermore achieved by a cross-connect module which comprises at least one optical filter according to the invention. By means of this, it is possible to provide a cross-connect module in which the reconfiguration can take place non-destructively. The possibility of controlling the transmission response of the optical filter by deliberately changing the temperature allows the filter action of the optical filter to be suspended by the appropriate temperature selection. At this moment, the filter does not in any way interfere with adjacent channels since no reflection takes place. Tuning of the filter can now advantageously be carried out. When the optical spectrum is being changed, adjacent optical spectra are crossed without causing any effect on the signals that may likewise be transported in this circuit over these optical spectra. It is hence possible to select a new channel without thereby influencing, or even interfering with, the channels or the signal flow which need to be crossed in doing so. After the desired new spectrum or channel has been reached, the reconfiguration is completed by resetting the temperature in such a way that the filter action restarts. This is preferably done by returning the difference in refractive index ($n_1 - n_2$) to a magnitude greater than zero by the temperature change.

A preferred cross-connect module of the present invention comprises at least one add-and-drop module. By

means of this, it is possible to construct the cross-connect module from add-and-drop modules.

Another preferred cross-connect module of the present invention has at least one quad circulator and/or at least one Mach-Zehnder structure. By means of this, it is possible to reduce the number of circulators used.

A cross-connect device is preferably provided which contains a plurality of series-connected cross-connect modules of the present invention. By means of this, it is possible to cascade the circuit arrangements and hence interconnect even more lines.

In a preferred method of the present invention for the non-destructive tuning of a filter, the filter loses its filter characteristic as a result of a first temperature change, then the tuning of the filter is carried out, and then the filter regains its filter characteristic as a result of a second temperature change. This method permits non-destructive reconfiguration of purely optical network elements. The exploitation of the thermo-optical effect to influence the quality factor of the resonance of the filter makes it possible to adjust the filter, by a first temperature change, in such a way that it loses its filter characteristic. This is preferably done by adjusting the temperature-dependent refractive indices in such a way that the difference becomes zero. So long as the filter has been "switched off" in this way, the tuning of the filter can be carried out without influencing adjacent channels or channels which are crossed. Once the new channel has been reached, i.e. the filter has been tuned to the new optical spectrum, the filter is "switched on" again by a second temperature change. In doing so, the temperature is preferably changed in such a way that the refractive indices again have a predetermined difference.

By means of this, a method for the non-destructive reconfiguration of purely optical network elements, in particular of the filter according to the invention, is procured.

The optical filters of the present invention are particularly preferably used for the production of a circuit having add-and-drop functionality; and/or a circuit having drop-and-continue functionality; and/or a circuit having multicast functionality; and/or a circuit having dual-homing functionality; and/or a circuit having cross-connect functionality. Multicast is the deliberate linking of a plurality of selected receivers to one transmitter (also referred to as group call). Dual homing is the connection of one receiver via two different network elements and paths. By means of this, it is possible to provide purely optical network elements which have the functionalities referred to above and are at the same time non-destructively tunable or reconfigurable.

The invention and other advantageous features will be described in more detail with reference to exemplary embodiments.

Figure 1 shows an add-drop-continue module,

Figure 2 shows an add-drop-continue module according to the invention,

Figure 3 shows a variant of this add-drop-continue module,

Figure 4 shows a possible filter construction,

Figure 5 shows the transmission diagram of the band-stop filter,

Figure 6 shows the transmission diagram of the band-stop filter in the case of a drop-and-continue function,

Figure 7 shows an add-drop-continue device having a series circuit in which a plurality of add-drop-continue modules are connected together,

Figure 8 shows a variant for the simultaneous extraction/injection of a plurality of WDM channels

Figure 9 shows a standard optical cross-connect module (OXC) having optical n x n space-switching subunits,

Figure 10 shows a schematic representation of a cross-connect module in WDM-systems,

Figure 11 shows cascaded cross-connect modules,

Figure 12 shows a circuit arrangement according to the invention of a cross-connect module,

Figure 13 shows another circuit arrangement according to the invention of a cross-connect module.

The add-drop-continue module represented in Figure 1 has already been explained in the introduction to the description. The splitter SP and the optical switch SW may be omitted if a tunable filter is being used which has resonant attenuation, so that a specific component of the energy of an optical signal, for example half said energy, is reflected and the remaining component is forwarded via the second circulator.

Figure 2 represents such an add-drop-continue module. It contains a first circulator ZI1, a tunable filter BSF and a second circulator ZI2. The transmission frequency of the filter can be continuously altered. The module can therefore be used for a plurality of wavelengths.

The attenuation of the filter can be changed by deliberately controlling the temperature, so that one signal range D_k is reflected by the filter and branched off, and the other signal component C_k is transmitted. It is hence possible to switch between the add-drop function and the drop-and-continue function using the same element, without optical switches being required. Of course, no signal is inserted in the drop-and-continue function (represented in Figure 2).

Figure 3 represents a variant of the add-drop-continue module, in which the second circulator has been replaced by a coupler KO. Although this variant is lees expensive, the coupler has greater attenuation.

If only the drop-and-continue function is to be produced, the second circulator or coupler may of course be omitted in a drop-and-continue module.

Figure 4 represents a possible embodiment of the filter in planar technology. The filter consists of an optically conductive material, generally quartz glass, and is essentially formed by a first region B1 having a temperature-dependent refractive index n_1 (t), (t - temperature), in which the essential energy component of the light is guided, and a second region B2 having a different temperature-dependent refractive index n_2 (t) regions. Only non-essential components of the light are guided in other regions, the substrate SUB and the superstrate SUP. They are hence only non-essentially involved in the filter action. The interface between the two regions 1 and 2 presents a wave structure of period λ, which has been produced by suitable diffusion or mechanical processing (grating). In the known fashion, this geometrical structure has a wavelength-selective transmission and reflection response, which is represented in Figure 5.

The resonant wavelength λ_k is essentially determined by the period of the interface; the transmission attenuation is determined essentially by, besides the grating length and the grating amplitude, the difference in refractive index $n_1 - n_2$.

The resonant wavelength λ_K can be altered by mechanical pressure P (represented by dashes in Figure 5). If, for example, a wavelength multiplex signal

λ_1, λ_2 ... λ_N (the same notation is used here for the optical signals as for the wavelengths) is fed into the filter, then one specific wavelength λ_K will be reflected whereas all the other wavelengths will be forwarded with very little attenuation.

A heating element HE can be used to heat the filter, so that the filter action is reduced and the transmission attenuation is decreased. A drop-and-continue function may be produced by setting an attenuation value of about 3 dB, as can be seen in Figure 6.

When the system is being reconfigured, the intention is for different optical signals, which have different wavelengths, to be branched off. By using the filter described above, this can be done without interfering with adjacent optical signals (or adjacent multiplex channels). The filter action is firstly removed by heating, so that all signals are forwarded. Tuning to the new wavelength is then carried out by exerting a mechanical pressure corresponding to this wavelength and subsequent cooling in order to restore the filter function, so that a different optical signal is now transmitted. Control circuits (not shown here) can be used to perform very accurate adjustment. Peltier elements may be used as heating and cooling elements.

Owing to their thermo-optical mechanism, these wavelength filters still have relatively high inertia. It is, however, already realistic to expect switchover times of from 10 ms to 500 ms, which is usually acceptable in the case of reconfigurations which are carried out infrequently.

In order for a plurality of optical signals λ_K, λ_{K+1} to be branched off and injected, a plurality of these modules Z1, BSF1, Z2, Z3, BSF2, Z4 are connected in series according to Figure 7.

Figure 8 shows an add-drop-continue module ZI1, BSF1, BSF2, BSF3, ZI2, in which a plurality of band-stop filters BSF1, BSF2, . . . BSFM are interposed between two circulators. According to the number of filters, a plurality of optical signals λ_1 to λ_M are simultaneously injected or extracted. Individual signals can be branched off or injected by using a demultiplexer DMUX a multiplexer MUX.

It should also be mentioned that the band-stop filter may also be produced with a larger bandwidth. Instead of individual channels, it is then possible to extract and inject channel groups comprising adjacent channels.

Figure 9 shows a solution for a standard optical cross-connect (OXC) having optical n x n space-switching subunits. In this case, demultiplexers DMUX are connected via optical conductors to a space-switching subunit of dimension n x n, which are in turn connected to multiplexers MUX. An incoming optical multi-wavelength signal is decomposed by the demultiplexer DMUX into a single-wavelength signal. These single-wavelength signals are subsequently switched by using optical space-switching subunits of dimension n x n. The forward-switched single-wavelength signals from the various space-switching subunits then reach the multiplexer MUX, where they are recombined to form an output signal.

In the case of a circuit arrangement having e.g. 64 wavelengths per multi-wavelength signal and 4 bidirectional conductor, 64 space-switching subunits of dimension 4 x 4 are needed.

By means of this arrangement, it is possible to switch each single-wavelength signal of an incoming conductor to any desired output conductor.

Figure 10 gives a schematic representation of a cross-connect module having bundled cross-connect functionality in WDM systems. In this case, wavelengths 1 to n arrive on line 1. The wavelengths 1 to i and 1 to m on lines 1 and 2 are connected together, m describing the maximum number of parallel wavelength signals per fiber in the WDM system and i and l being dynamically variable numbers in the range $1 \leq i \leq l \leq m$. Similar considerations apply for lines 3 and 4. This connection is indicated by the solid stroke. The dashed lines respectively represent the connection between line 1 and line 3, and between line 2 and line 4, for the wavelengths i to j and k to l, where i, j, k, l are dynamically variable numbers in the range $1 \leq i \leq j \leq j \leq k \leq l \leq m$.

The dotted lines represent the connections between lines 1 and 4, and between lines 3 and 2, in which the wavelength bundles j to k are switched together, where i, j, k, l are dynamically variable numbers in the range $1 \leq i \leq j \leq j \leq k \leq l \leq m$.

Using this circuit arrangement, it is possible to interconnect wavelength bundles in WDM systems with a cross-connect functionality.

Figure 11 gives a schematic representation of cascaded cross-connect modules. By connecting circuits of Figure 10 in succession, it is possible to produce more comprehensive cross-connect functionalities in WDM systems. Two such circuits have been cascaded in Figure 11, but it is also possible to cascade other circuits and use them in double-star topology, star topology or in meshed networks.

Figure 12 represents a circuit arrangement according to the invention with bundled cross-connect functionality. Four

conductors L1 to L4 are represented, which can be interconnected together. Circulators ZI1 to ZI12 are furthermore provided. These are triple circulators. Optical filters according to the invention are furthermore provided as band-stop filters BS1 to BS6.

The way in which the circuit operates will be explained with reference to the division of the signals arriving on L2 according to the cross-connect functionality represented in Figure 10.

The incoming multi-wavelength signal on L2 is completely forwarded via the optical circulator ZI1, in the direction of the arrow, toward the next gate and encounters the optical band-stop filter BS1. This filter reflects the wavelength channels OCH i to l that are to be extracted, and the remaining channels are transmitted. In the same way, the wavelength channels i to l are extracted from the lines 1, 3 and 4.

The multi-wavelength signal (i to l) that is extracted on L2 is completely forwarded via the optical circulator ZI5, in the direction of the arrow, toward the next gate and encounters the optical band-stop filter BS3. This filter reflects the wavelength channels OCH j to k, and the remaining channels are transmitted. The multi-wavelength signal that is extracted from line 1 and forwarded to the circulator ZI6 is reflected from the same optical band-stop filter BS3. Conversely, the transmitted wavelength channels OCH i to j and OCH k to l are exchanged at the band-stop filter BS3. The same principle is used to process the wavelength bundles extracted from line 3 and line 4.

The multi-wavelength signal coming from the circulator ZI5 is fed via the circulator Z12 to the line L4. In a similar way, the multi-wavelength signals coming from the circulators ZI6, ZI7, ZI8 are fed to the appropriate line.

The band-stop filters BS1 to BS6 are of broadband design, so that they cover a plurality of wavelength channels. If one of the filter edges lies outside the wavelength spectrum, then this situation can be used to produce a high-pass or low-pass function. The selection of a wavelength bundle is made possible by the adjustment parameter f at the band-stop filter, which is labeled with the corresponding indices. The "neutralization" of the filter may preferably be performed during reconfigurations by means of the transmission attenuation d.

By using the optical filter according to the invention in this circuit arrangement, it is possible to extract variable complete wavelength bundles from a multi-wavelength signal.

Figure 13 represents a similar circuit arrangement to Figure 12, but in which the triple circulators have been replaced by quad circulators. By means of this, it is possible to replace the 12 circulators which were used in the circuit arrangement according to Figure 12 by 8 quad circulators. The circulators may also be replaced by Mach-Zehnder structures.

By means of this, simple allocation of selected multi-wavelength bundles to different multi-wavelength channels is possible. The complexity of the system is reduced, in comparison with cross-connect modules of the prior art according to Figure 9, to a commensurately greater extent when the number of parallel wavelengths that are to be extracted per conductor is high. In the case of a circuit arrangement having e.g. 64 wavelengths per multi-wavelength signal and 4 bidirectional conductors, the solution variant having space-switching subunits and de-/multiplexers requires 64 space-switching subunits of dimension 4 x 4, whereas only 6 band-stop filters need to be used in the circuit arrangements proposed in Figures 12 and 13.